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Nihon University, College of Science and Technology.

n=1 Mode Motion on Field Reversed Configuration Plasmas

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Background (n=1 mode motion)

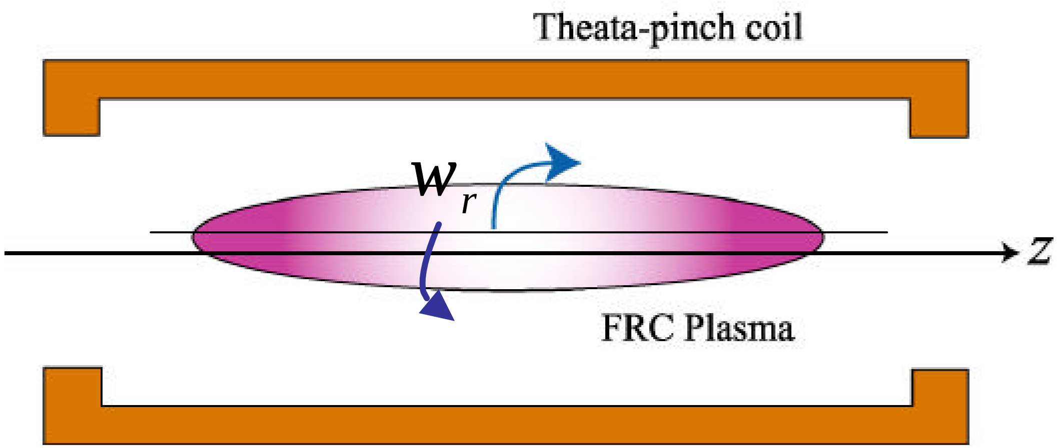
n=1mode motion of plasma column

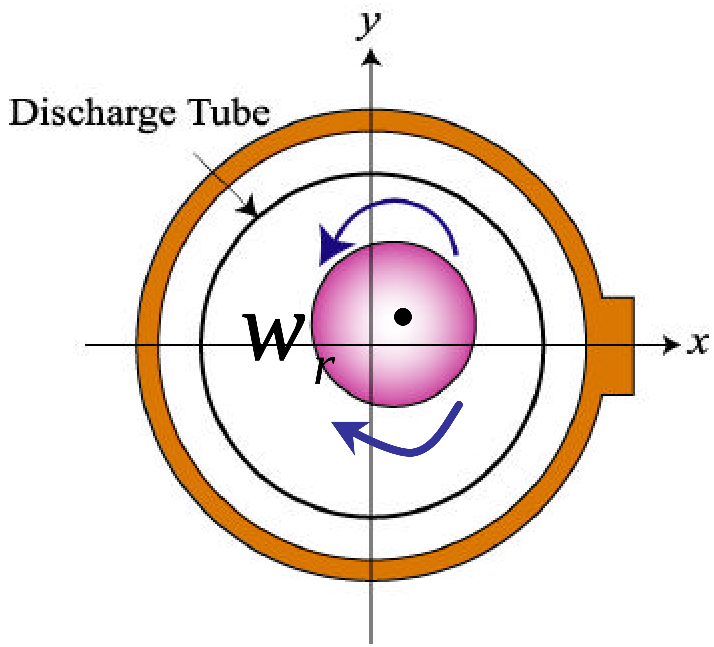
A field-reversed configuration (FRC) plasma deviates from its equilibrium position and moves slowly around it at an equilibrium phase.

$$r_s(z,q) = r_{s0}(z) + x(z)\exp(i(wt - nq)) \qquad w = w_r + ig$$

ξ(z)=const : **shift motion**   Rotational mode: **wobble motion**

ξ(z)=ψz: **tilt motion**





Effect of the n=1 mode motion

- Low reproducibility on a translation experiment (FIX, FRX-C/T)
- Particle loss from X-points
- Low efficiency on a neutral particle beam heating

- **Physics issue**

  Source and Driving Mechanism

- **Technology issue**

  Control method

  a multipole field (NUCTE)

  a neutral beam injection (FIX)

Purpose of this subject

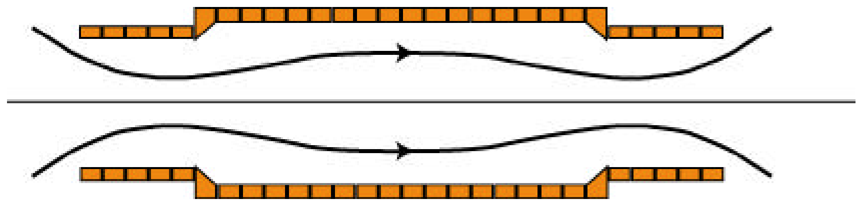
A source of the n=1 mode motion **is investigated from the point view of *a magnetic structure of the confinement field*.**

Contents

1. Magnetic Structure of the confinement field for a field reversed configuration
2. Experimental set up
3. Experimental results
   - Behavior of n=1 mode motion
   - Source of n=1 mode
4. Summary

1. Structure of Magnetic Field for FRC

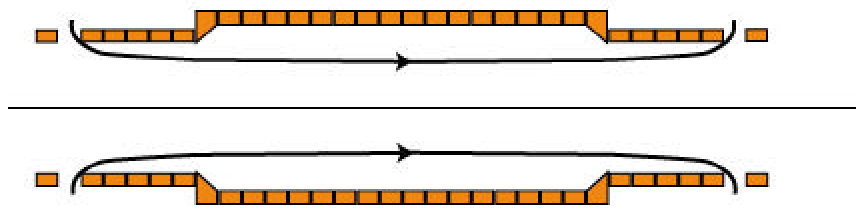
(a) Mirror coil



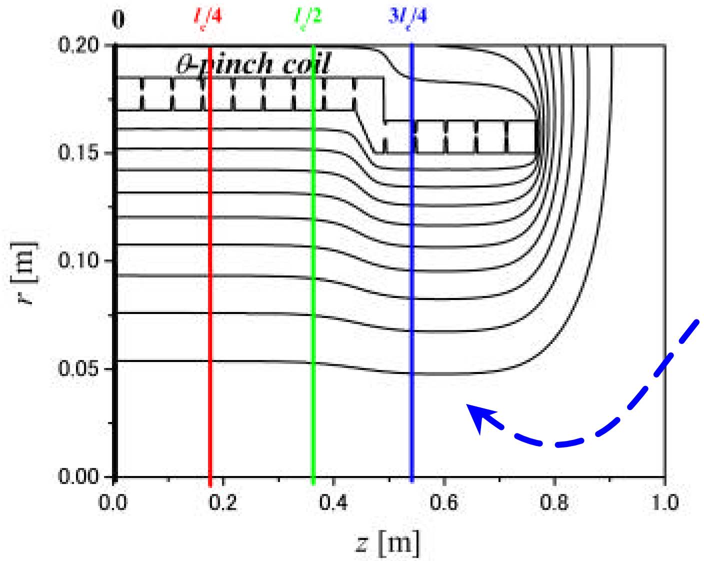
Negative field gradient of a radial direction

Shaping of a magnetic field line

(b) **Mirror coil with conducting rings, cusp bias field (Non-Tearing reconnection)**



Structure of Magnetic Field in q-Pinch Coil



Lines of magnetic force

$$\overline{B} \equiv \frac{2}{l_c}\int_0^{l_c/2} B_e dl$$

$$\overline{B}/\overline{B}_w(r)$$

Radial distribution of <u>magnetic field strength averaged along the line of magnetic force</u>

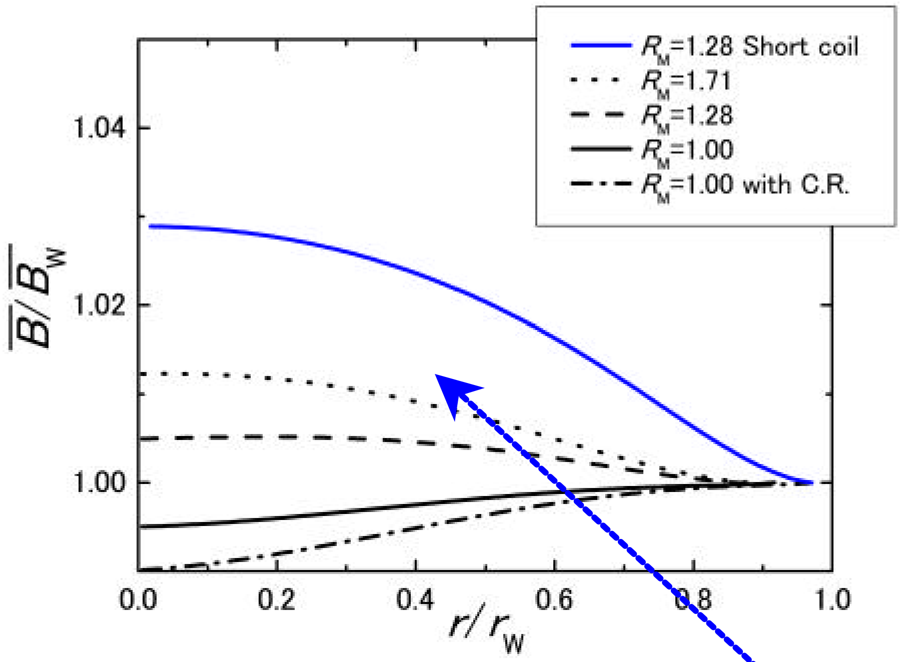
$$\Delta = \frac{\P}{\P r}\left(\frac{\overline{B}}{\overline{B}_w}\right) \approx \frac{\overline{B}(r_w)-\overline{B}(r_s)}{\overline{B}(r_w)}\frac{r_w}{r_w-r_s}$$

Radial gradient of the averaged Field

Magnetic Structure w/o and with FRC Plasma

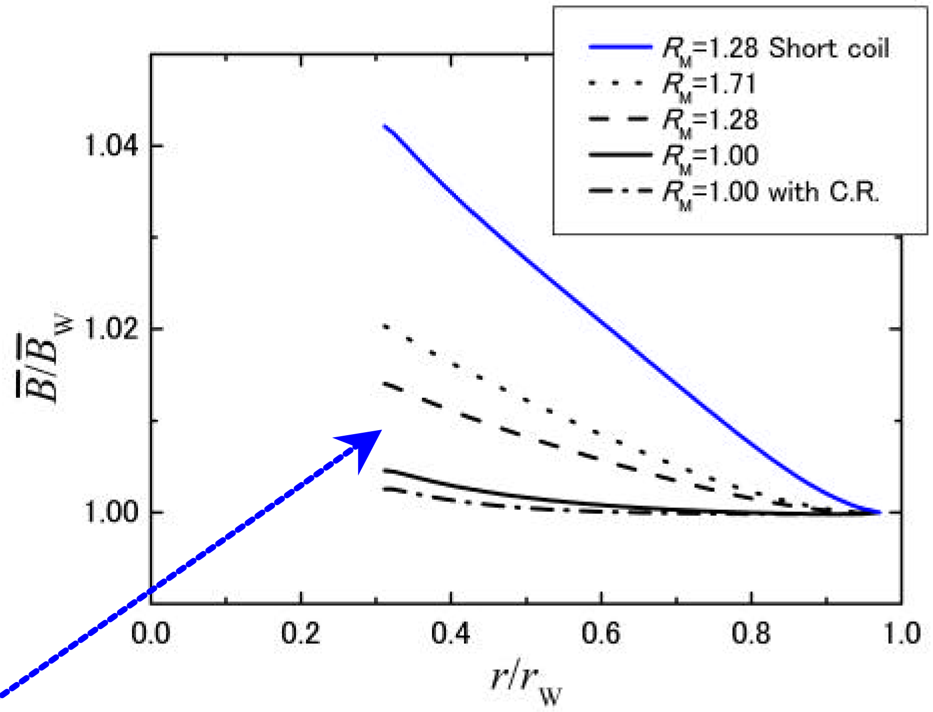
$$\frac{\overline{B}}{\overline{B}_W}$$

w/o FRC Plasma



with FRC plasma

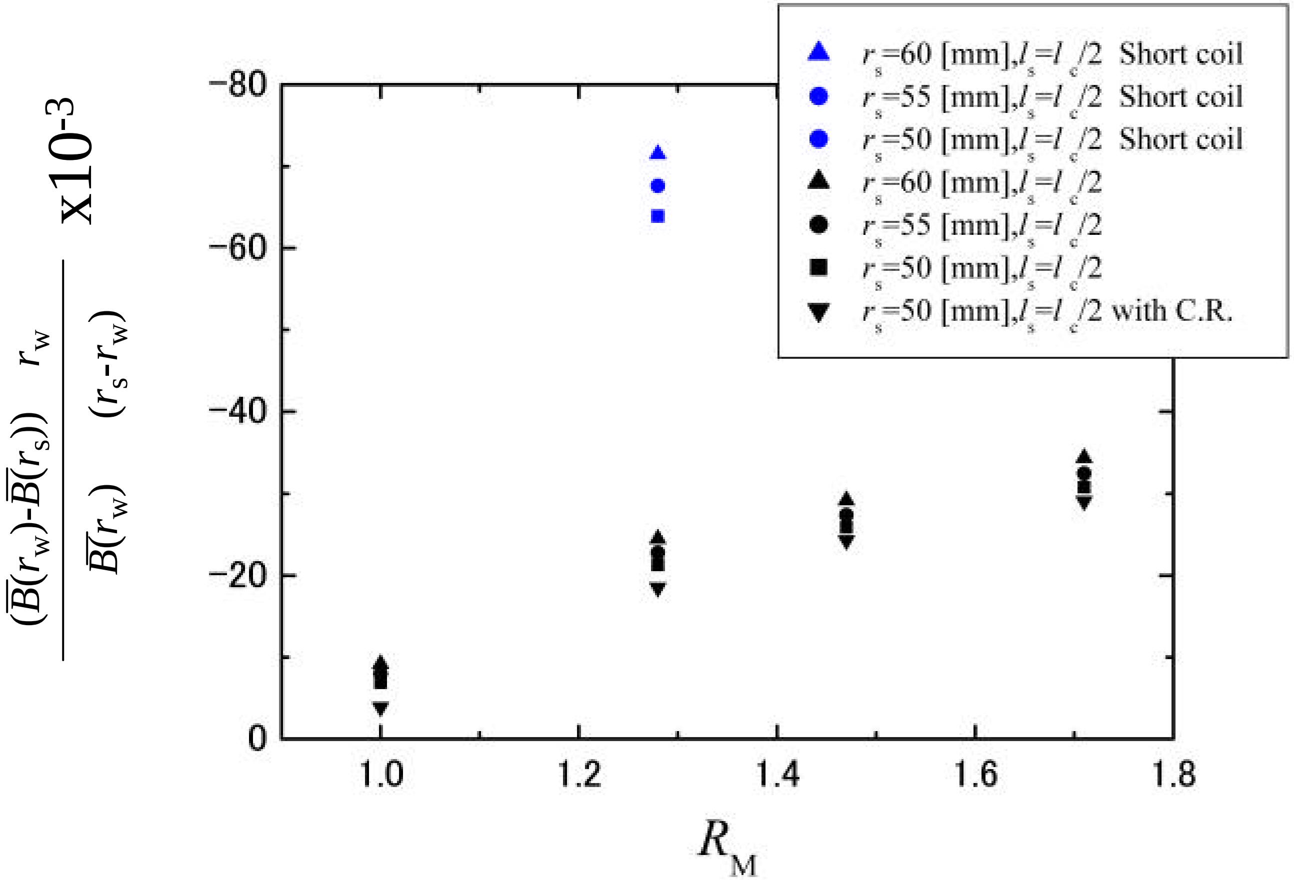
(l_s=37.5cm, r_s=5.0cm)



$$\boxed{\frac{\partial}{\partial r}\left(\frac{\overline{B}}{\overline{B}_w}\right) < 0}$$

negative gradient of magnetic field strength

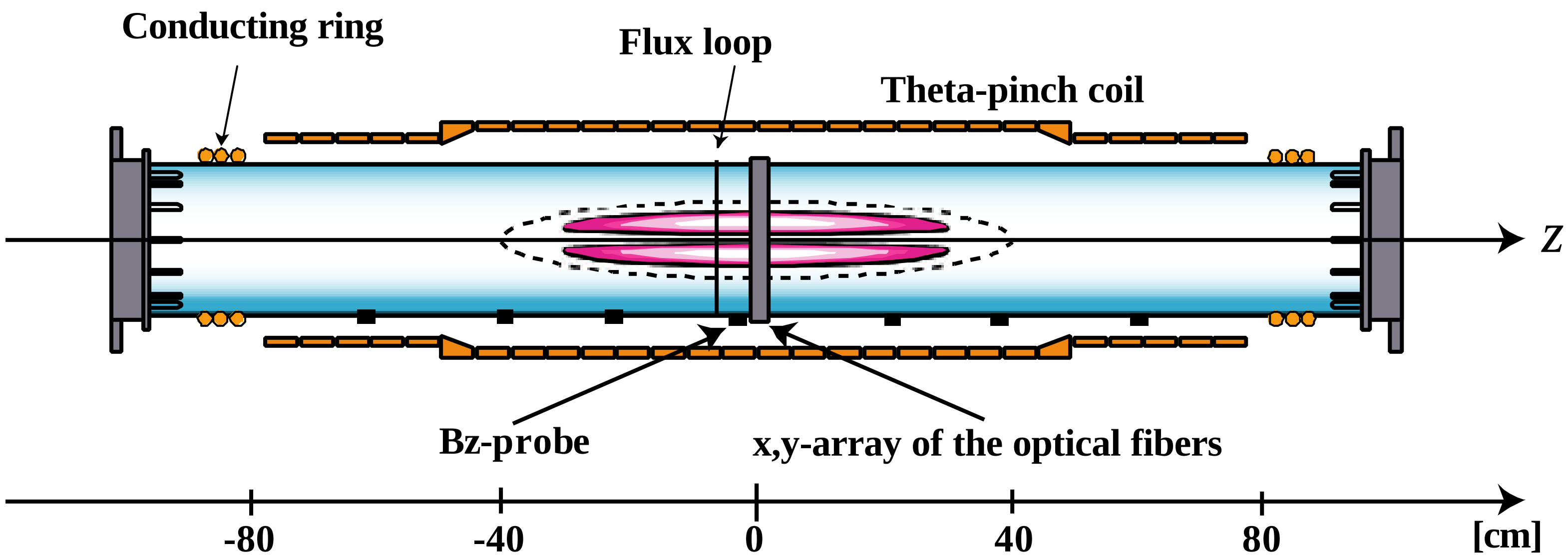
Magnetic structure Δ

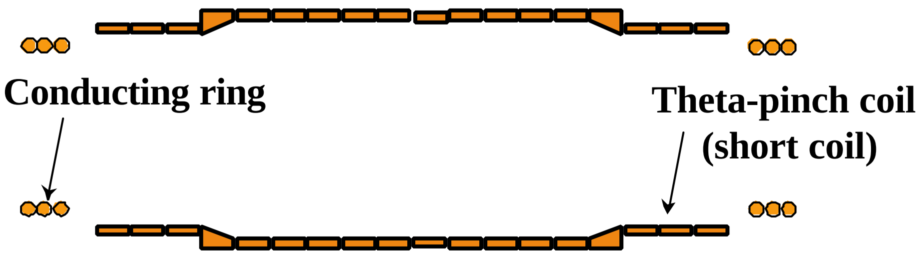


Magnetic field gradient ***at the outside of the separatrix is <u>negative</u>*****.**

Plasma elongation*, *Mirror ratio*, *Coil aspect ratio

2. Experimental Set up

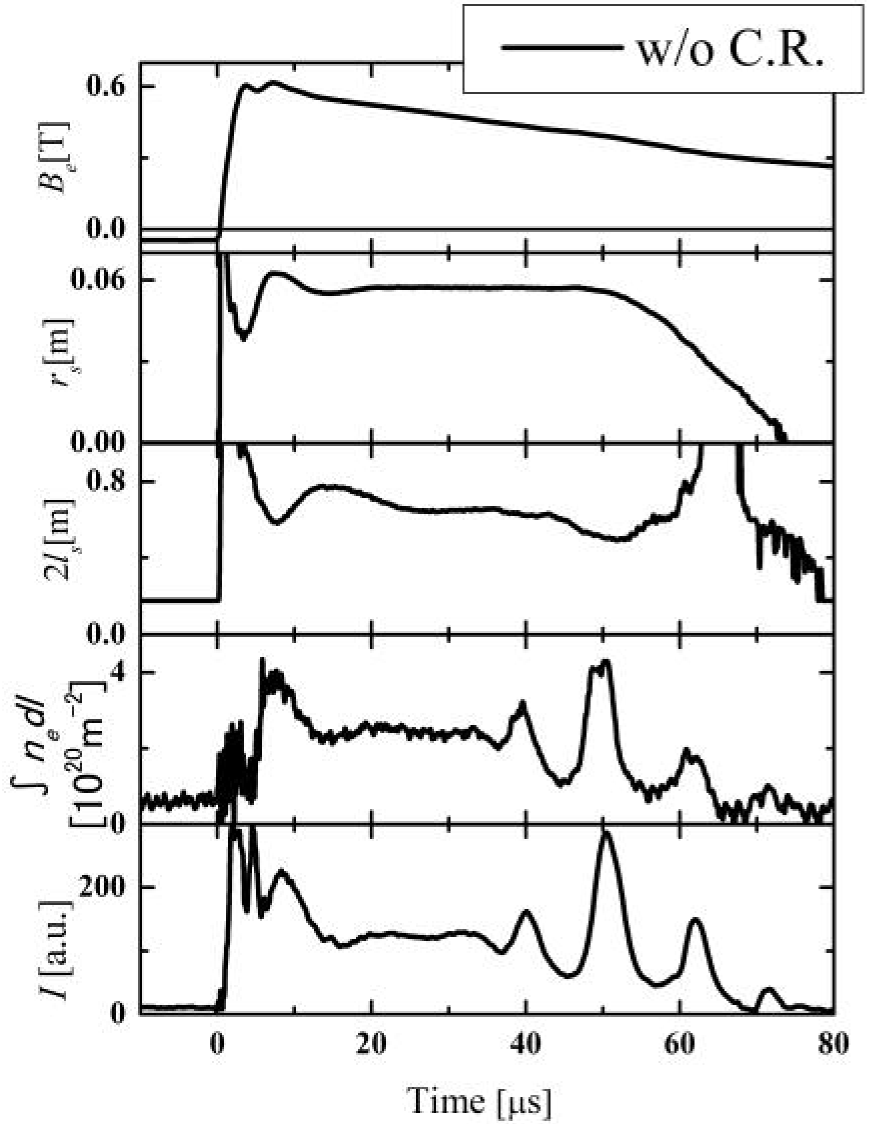




1. Installation of a conducting ring
2. Control of coil aspect ratio
3. Control of plasma elongation

1. Optical diagnostics
2. B_θ magnetic probe array

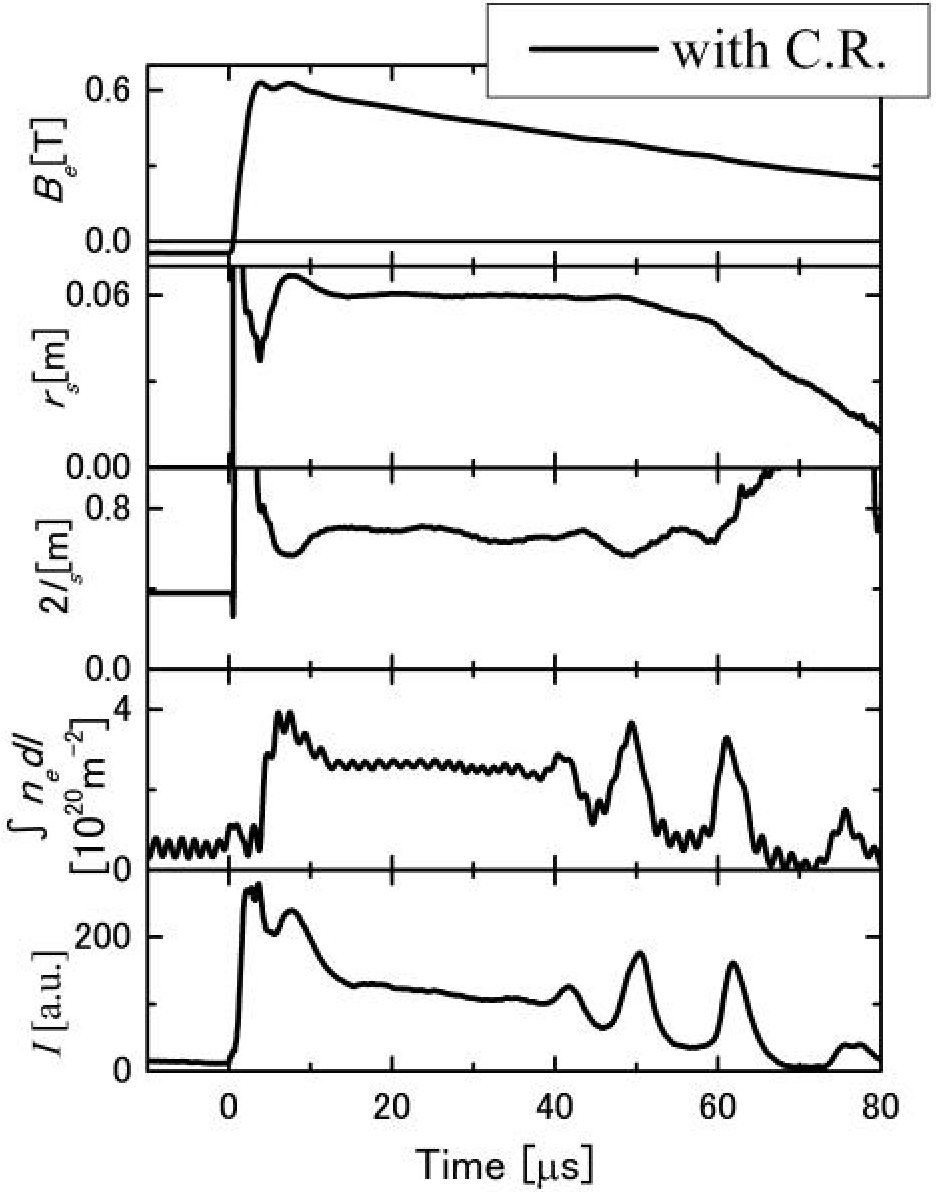
3. Typical Plasma Parameter w/o C. R.



Equilibrium Plasma Parameters

B_b=48mT
B_e=0.5T
r_s=0.057m
l_s=0.33m
n_e=2.1x10^{21}m^{-3}
T_i+T_e=280eV
b_s=0.7
r_i=0.0041m, w=4
τ_{life}=70μs
τ_{onset}=35μs
ω^*=4.2x10^{5}rad/s
V_A=170km/s (94km/s)

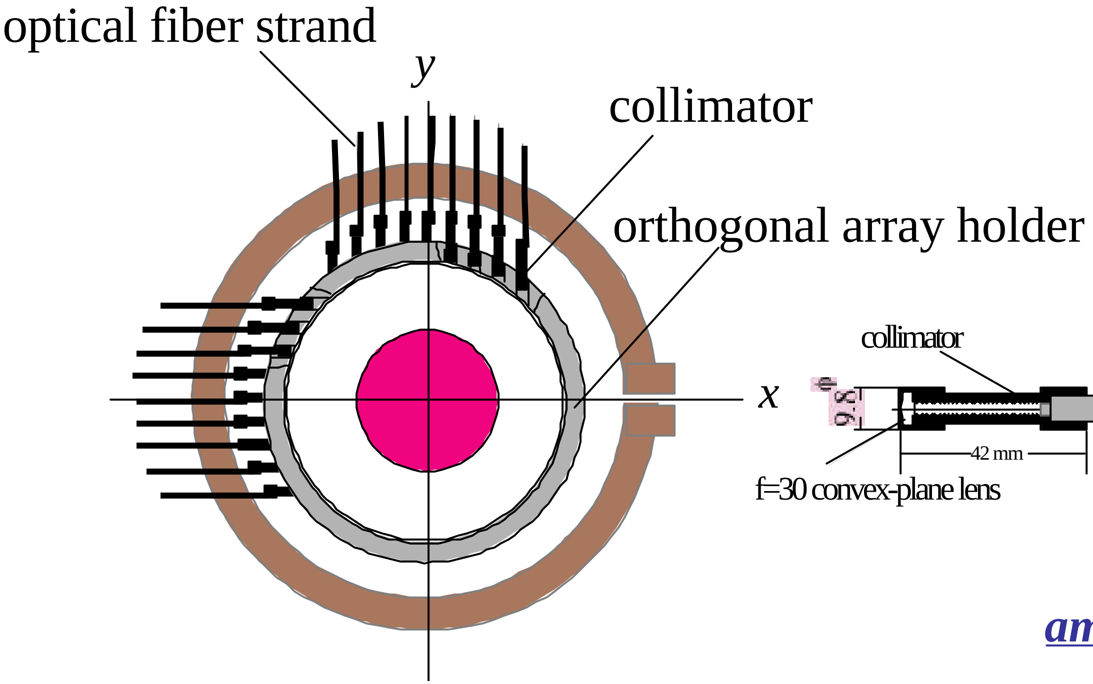
Typical Plasma parameter with C. R.



- All field lines are pulled out through the discharge tube from narrow regions near the coil ends due to the conducting rings.
- Closed field configuration is quickly formed at the coil ends as soon as the confinement field is applied.
- A long FRC is generated without tearing at the mirror regions.

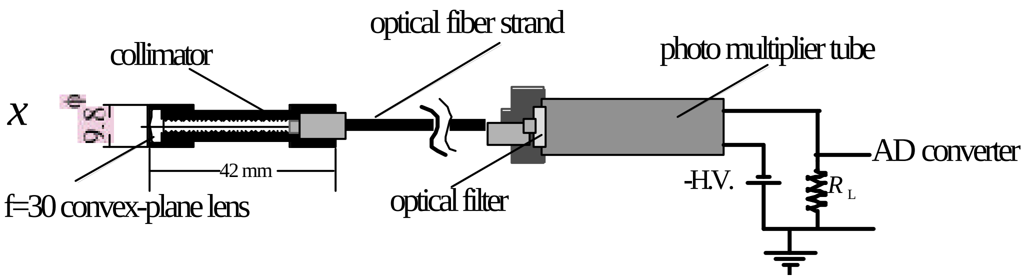
- Oscillation of r_s, l_s, and n_e decrease.
- Life time will be prolonged
- Onset of n=2 will be delayed
- Improvement of symmetry for FRC formation

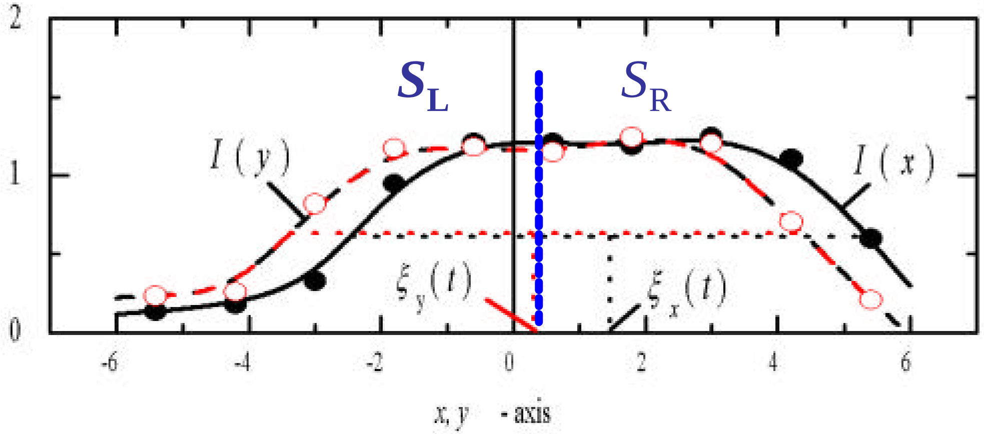
Observation of n=1 mode motion by visible optical diagnostics



Bremsstrahlung

$$I_l \propto \frac{z^2 n_e n_i}{T_e^{1/2} l^2} \quad (l = 550 \pm 5 \text{ nm})$$





amplitude

$$\left(x_x(t), x_y(t)\right) \quad x_r(t) = \sqrt{x_x^2(t) + x_y^2(t)}$$

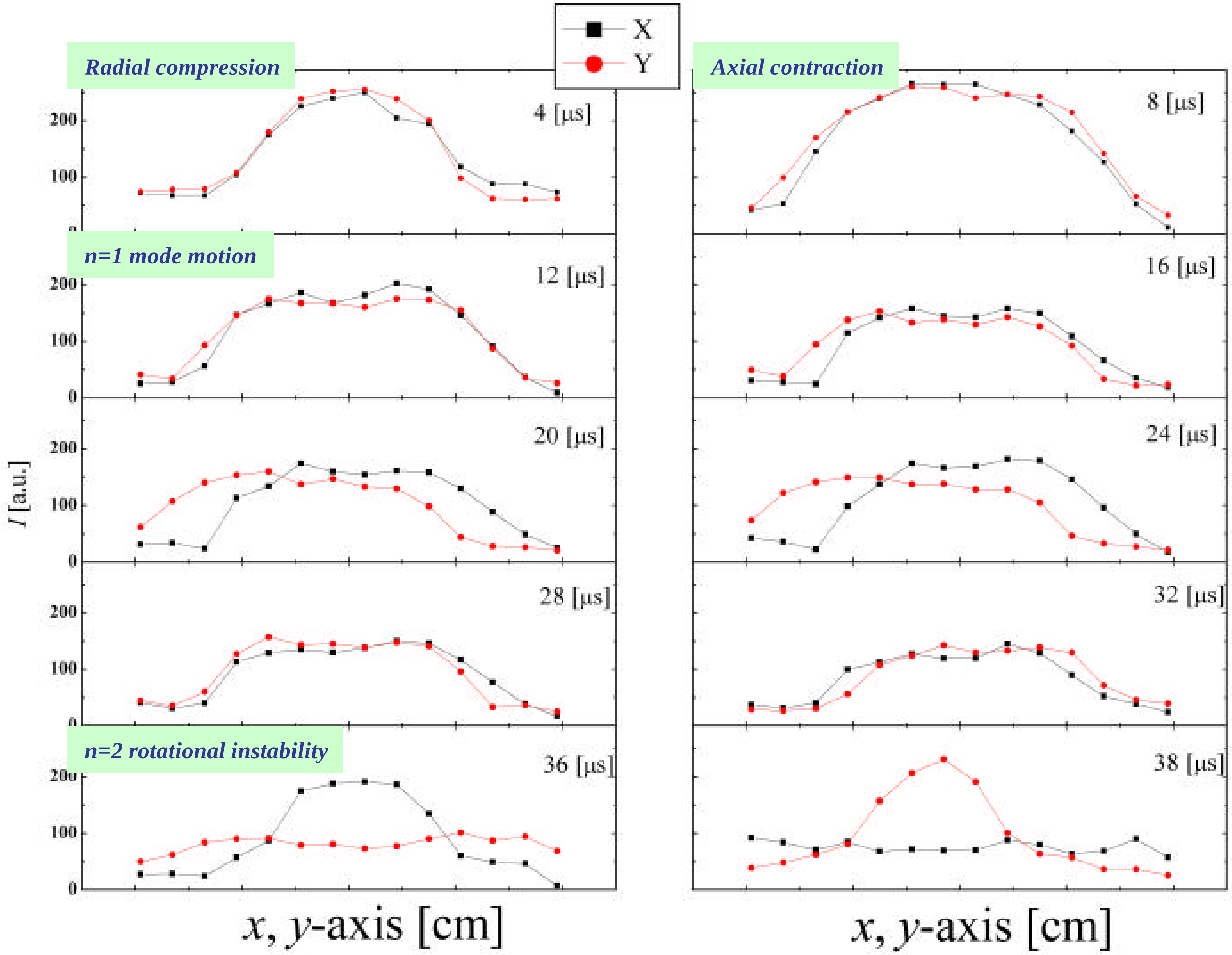
asymmetry

$$\Delta = (S_R - S_L)/(S_R + S_L)$$

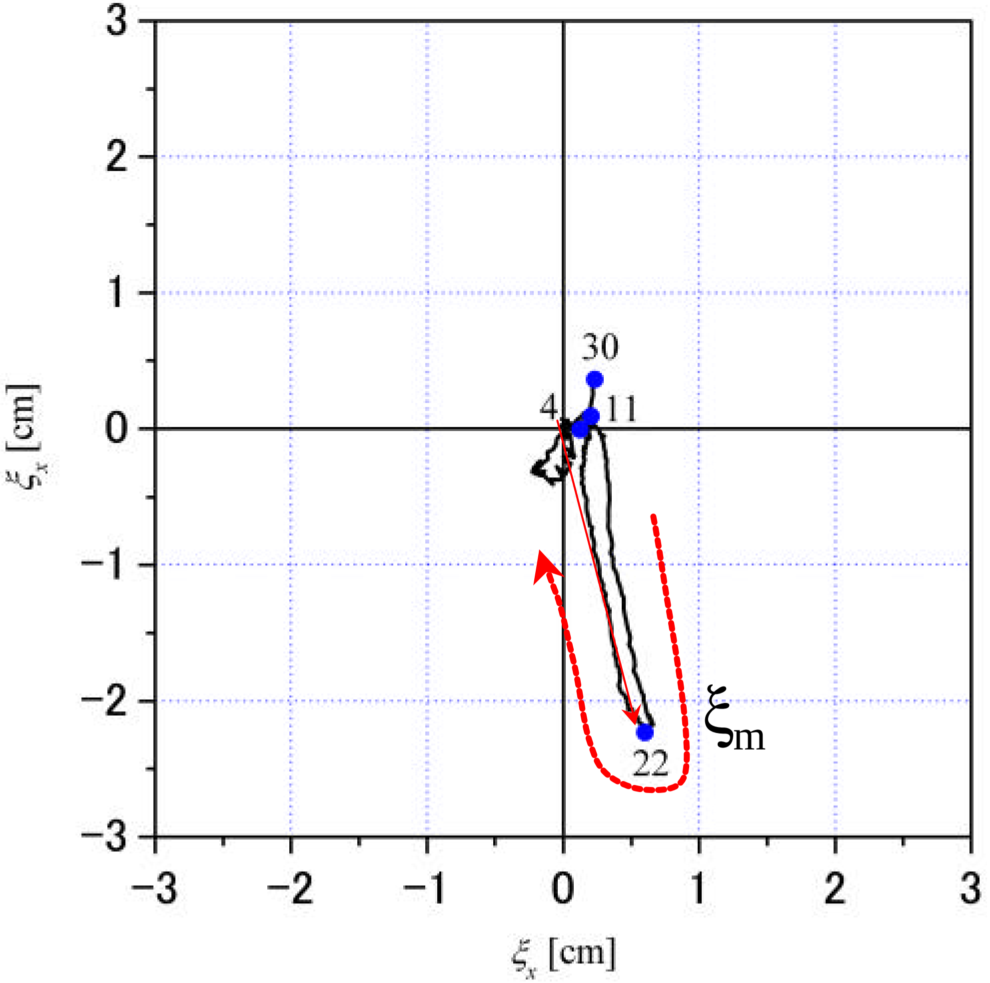
$$S_L = \int_{r_w}^{x_x, x_y} I(x)\,dx, dy$$

$$S_R = \int_{x_x, x_y}^{r_w} I(x)\,dx, dy$$

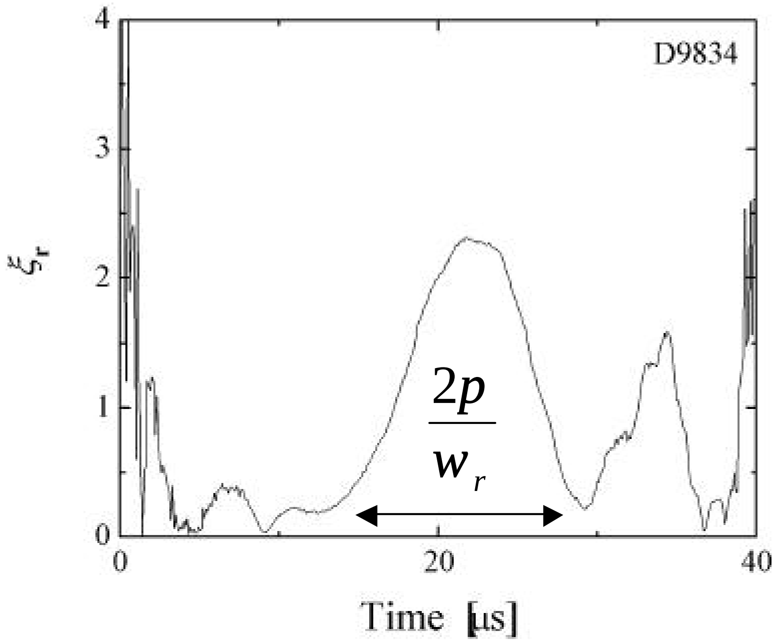
x-y profiles of line integrated light intensity at z=0



Trajectory of the Plasma column at z=0

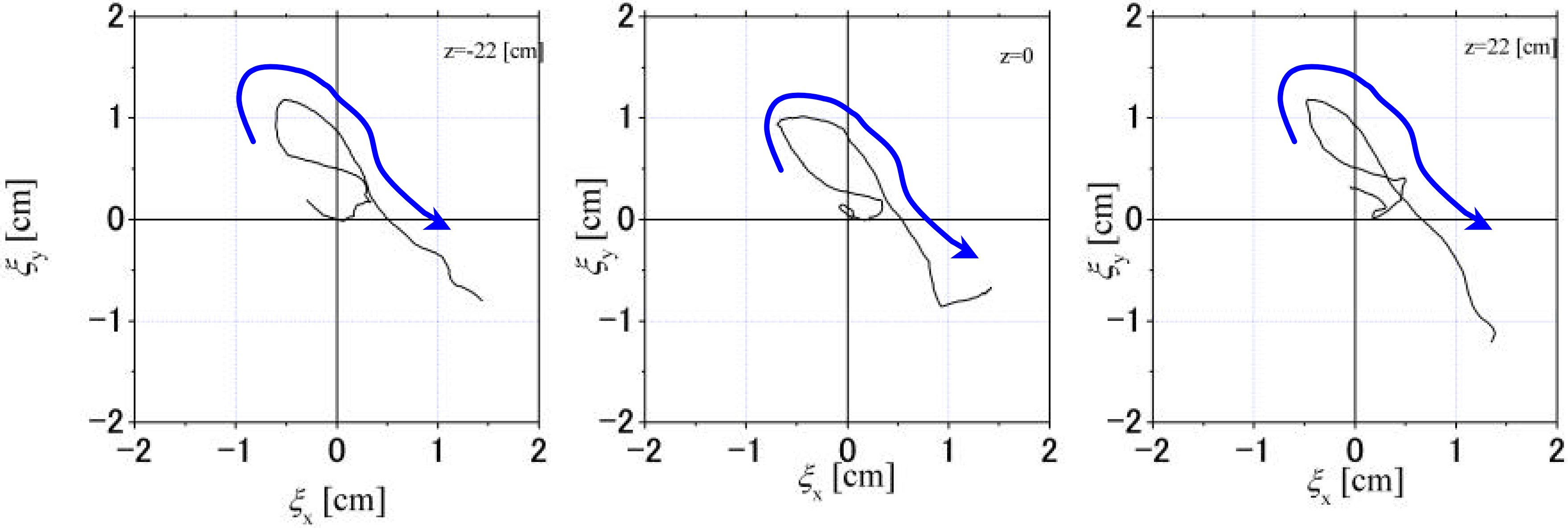


$$g = 0.36\times10^{6} \quad (s^{-1})$$
$$g^{-1} \geq t_A$$
$$w_r = 4.20\times10^{5} \quad (s^{-1})$$
$$w_r \approx \Omega^{*}$$



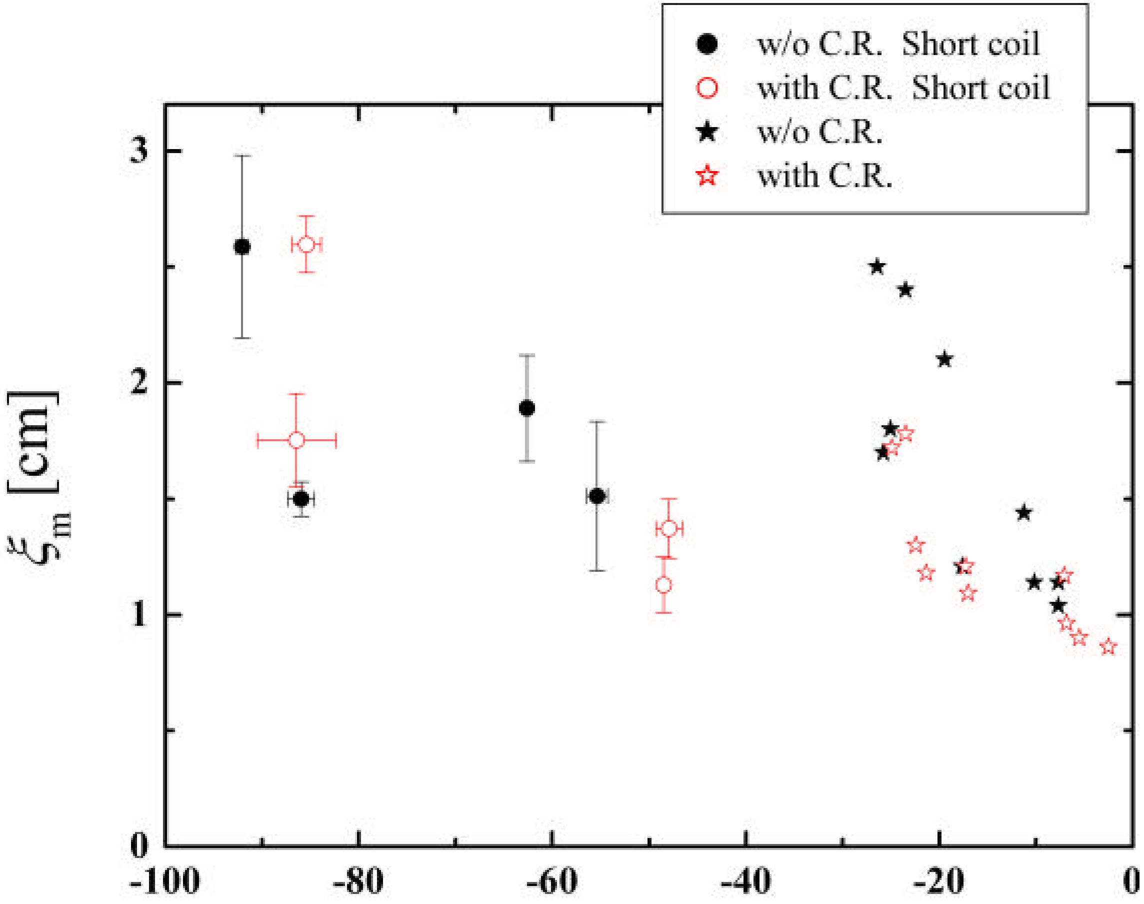
After the ***axial contraction***, n=1 mode motion is appeared

3-D trajectory of n=1 motion



Even mode (radial shift motion)

Dependence of x_m on averaged magnetic field gradient

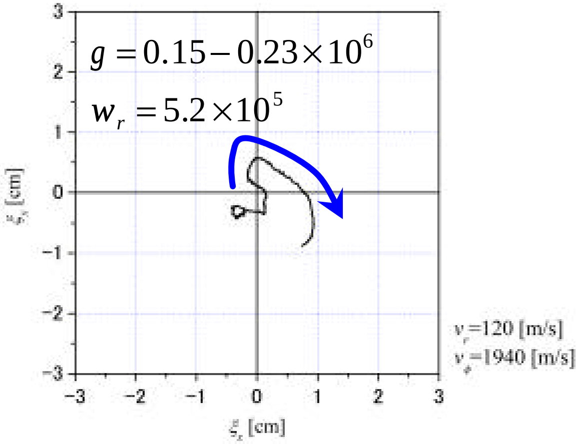


$$\frac{\overline{B}(r_w)-\overline{B}(r_s)}{\overline{B}(r_w)}\frac{r_w}{r_w-r_s}\times 10^{-3}$$

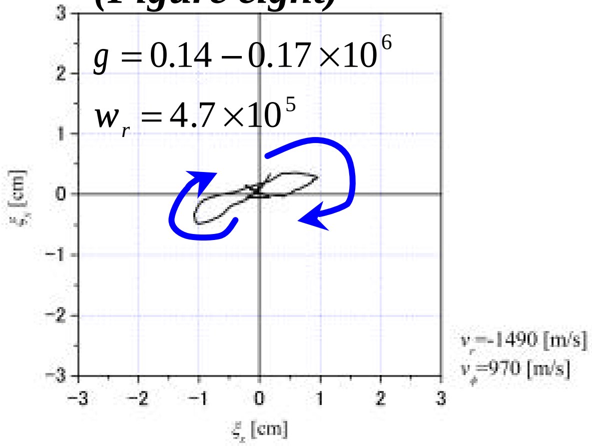
ξ_m ***increases with the radial gradient of the confinement field***

Typical Trajectory of Plasma column (r_s=5.7cm, l_s=37.5cm)

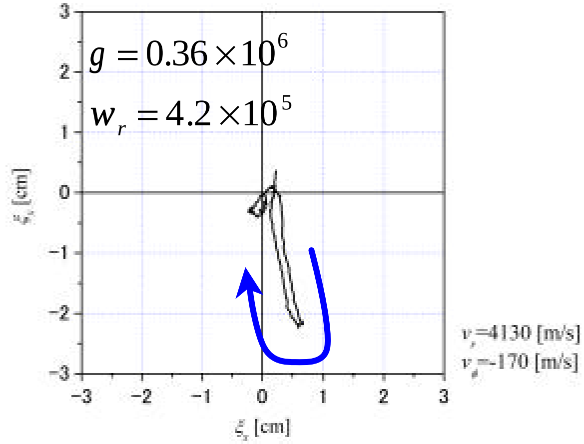
combined



Radial oscillation (Figure eight)

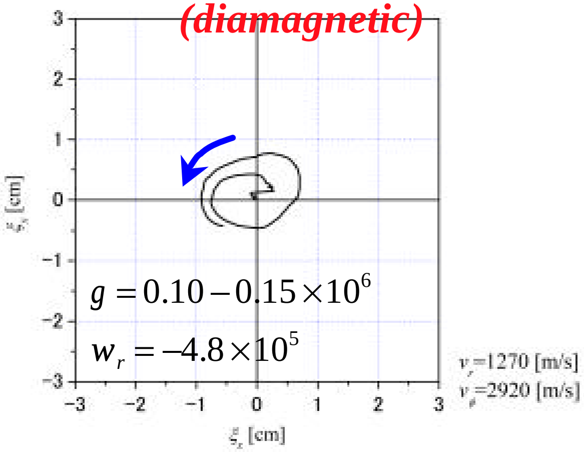


Radial oscillation



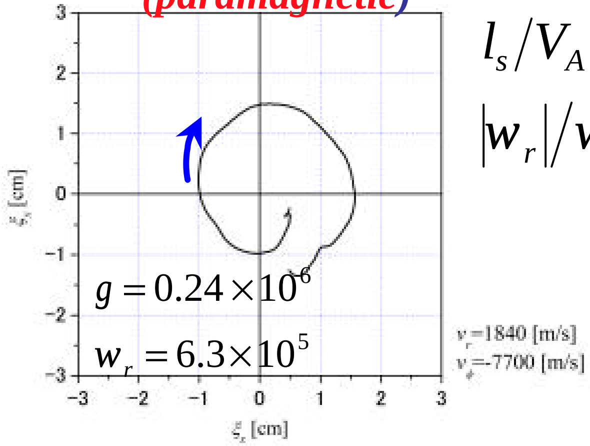
Rotation (counterclockwise)

(diamagnetic)



Rotation(clockwise)

(paramagnetic)



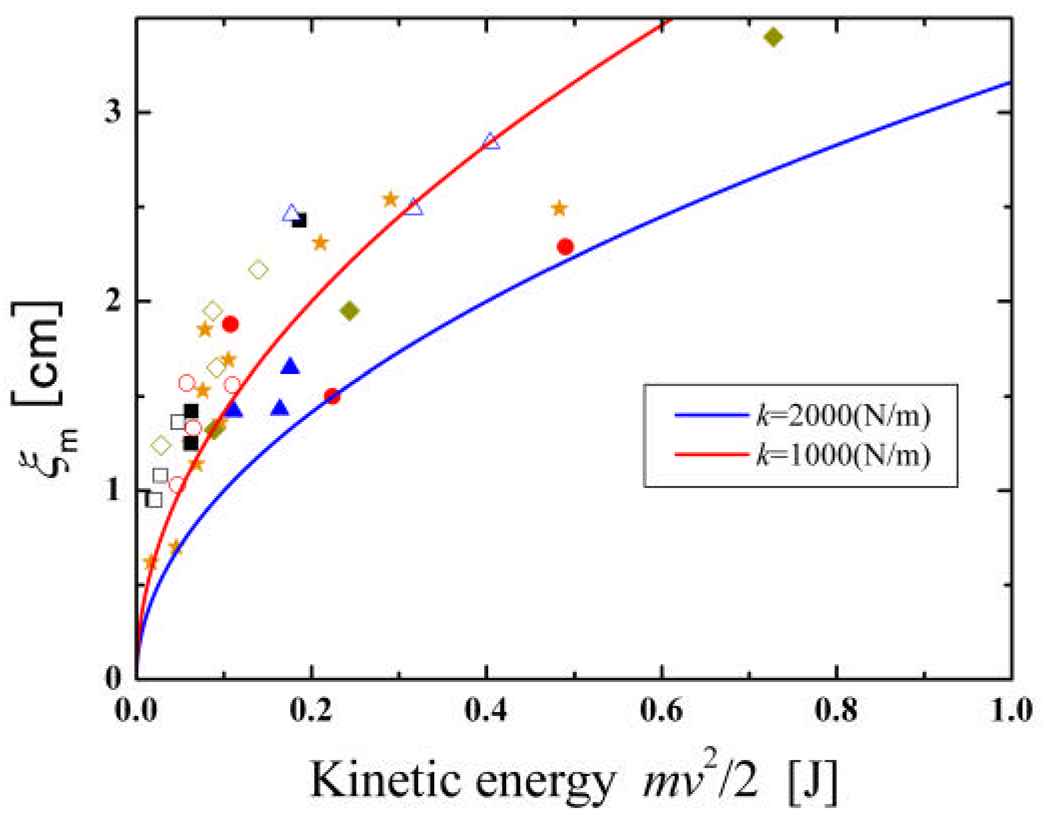
$$l_s/V_A \approx 2 \sim 4ms << g^{-1} \approx (5 \sim 10)t_A$$

$$|w_r|/w^* \approx 1.0 \sim 1.5$$

$v_r >> |v_q|$ *radial oscillation*

$v_r << |v_q|$ *Rotation*

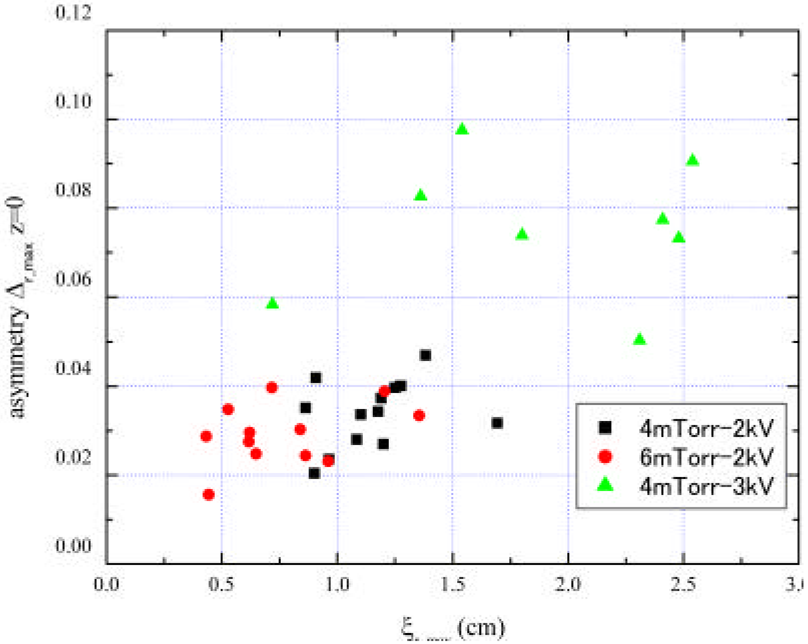
Estimation of the force acting on the plasma



k (center force) is ~1000 N/m (10N at x_m=0.01m)

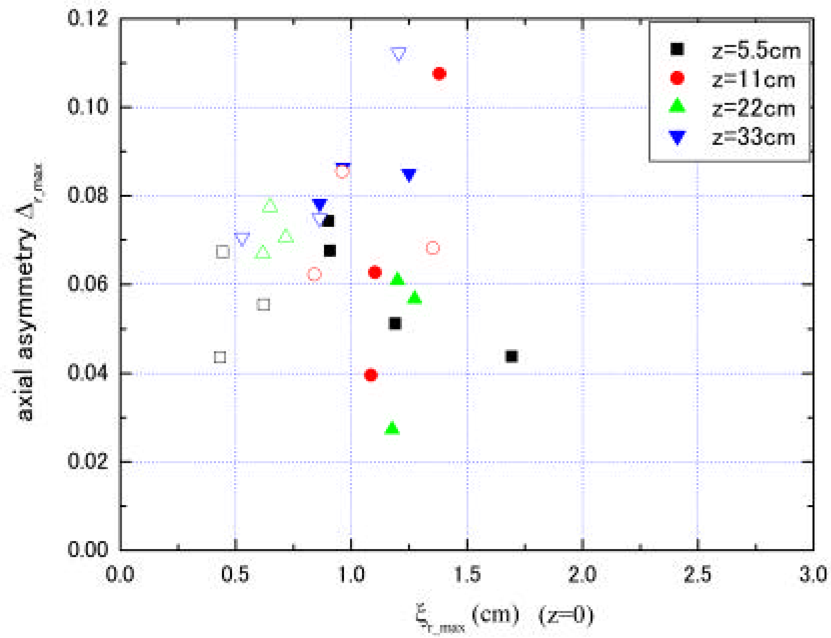
Relation between ξ_m and axial asymmetry

Relation between x_m and asymmetry at z=0



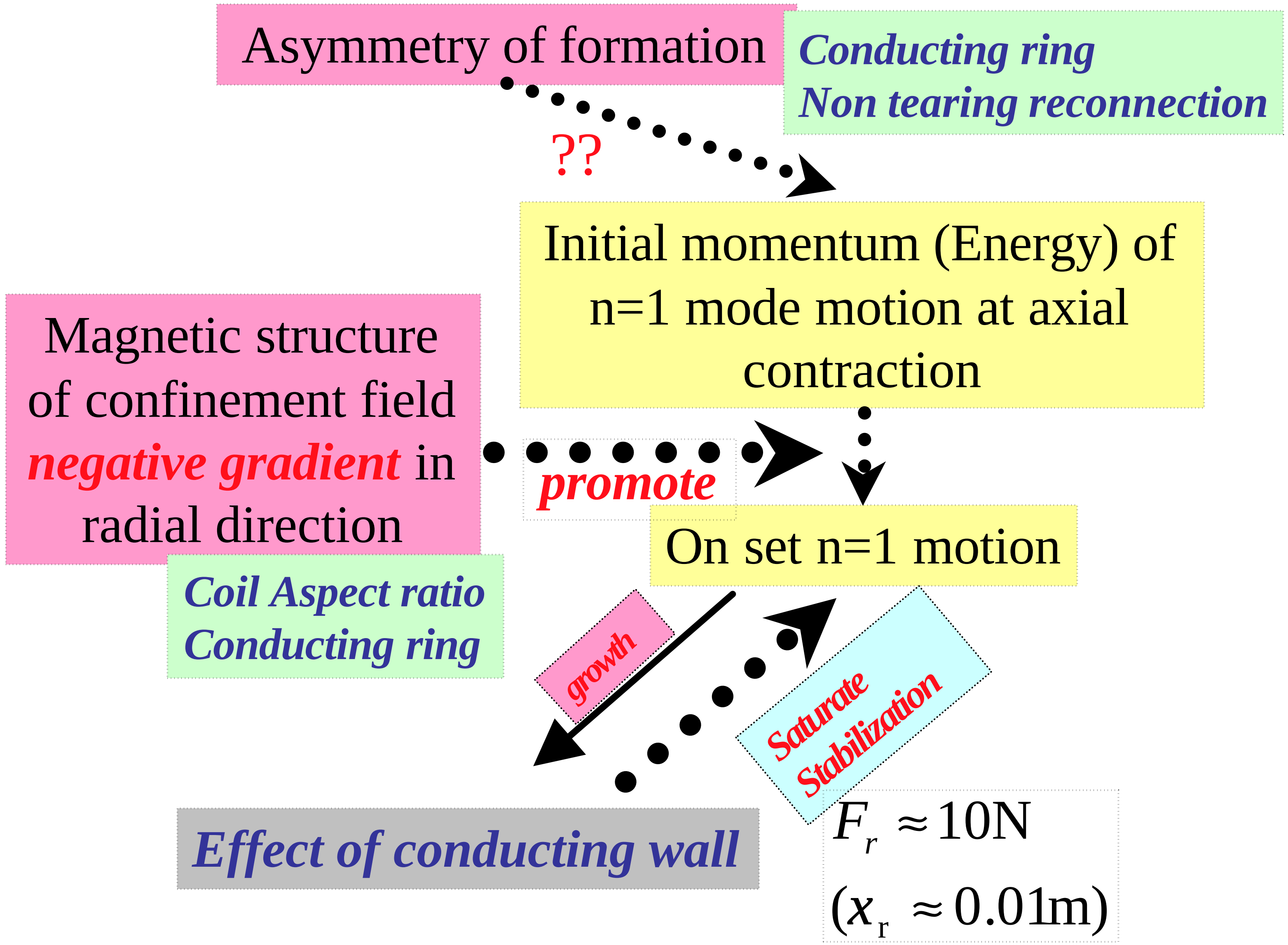
Relation between x_m and Axial asymmetry

Open symbol 6mTorr-2kV
Closed symbol 4mTorr-2kV



Weak correlation between x_m and axial asymmetry

Mechanism of generation and saturation for n=1 mode motion



4. Summary

1. **A source of n=1 mode motion** is investigated from point view of **a magnetic structure of a confinement field**.

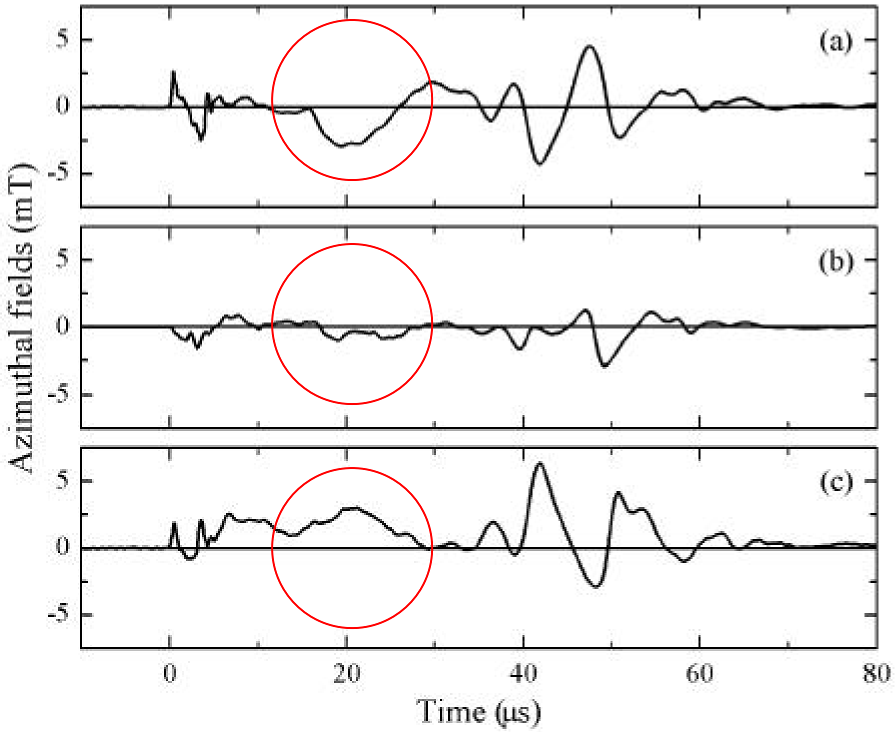
- The source of n=1 mode motion is related to ***an negative field gradient of a radial direction***. ***With the increase of the negative gradient, the amplitude of the motion becomes large.***
- The gradient is controlled by ***a coil aspect ratio and a plasma elongation***.
- By ***an installation of a conducting ring*** at the end of theta pinch coil, the amplitude decreases.
- ***Symmetry of a plasma formation*** is also related to the appearance of n=1 mode motion.

2. **Behavior of n=1 mode motion** is also investigated.

- The trajectory of n=1 mode motion depicts different orbits, for example, ***a radial oscillation, an elliptic (or circler)rotation and a combined orbit*** dependent on the initial velocity.
- The direction of the rotation is not only ***clockwise*** but also ***counterclockwise***.
- ***The axial mode structure is even.*** The odd mode motion can not be observed.

n=1 mode motion
by B_θ field measurements

Axial dependence of B_q field



z=-0.175m
q=-60°

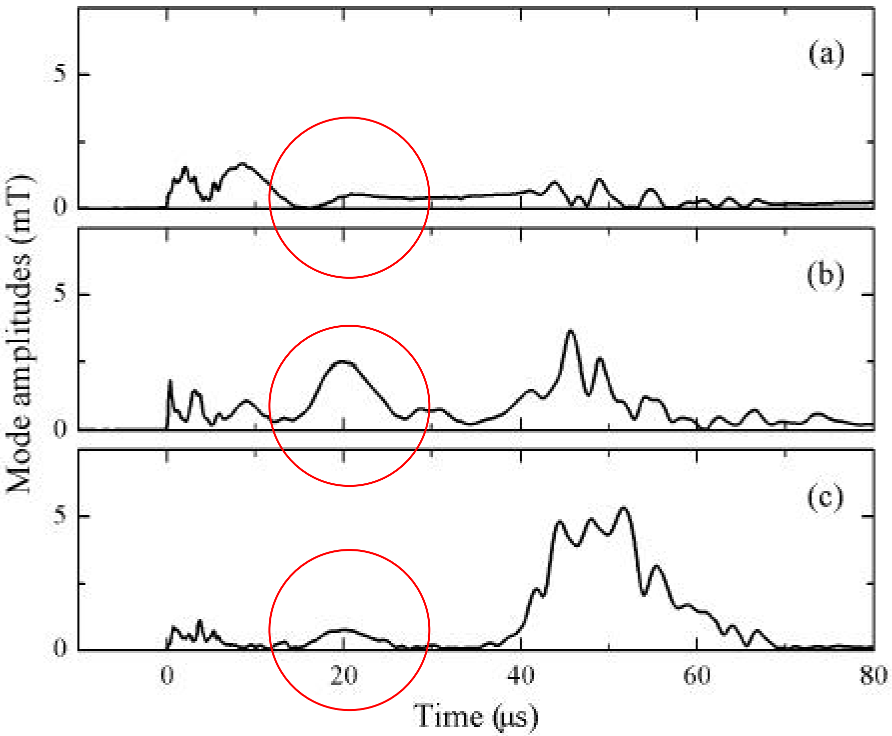
z=0
q=90°

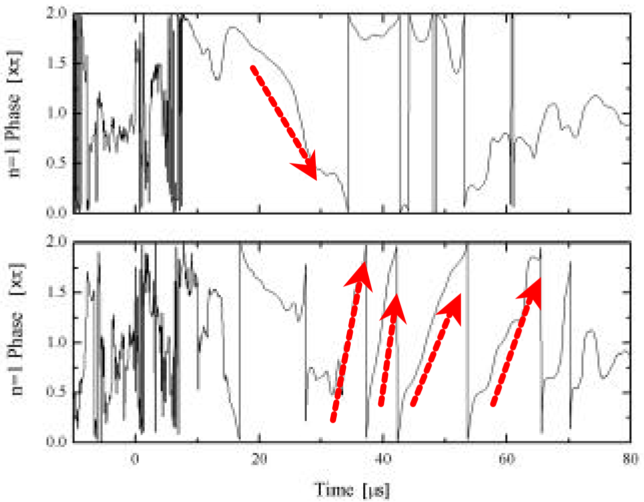
z=0.175m
q=-60°

Odd mode
of B_θ field

Even mode deformation
of Plasma column

Mode Analysis of B_q field at z=-0.175m





n=1 mode B_θ is dominant mode during 15-25μs

Estimation of Trajectory by a center of force

$$m\left(\frac{d^2r}{dt^2}-r\left(\frac{dq}{dt}\right)^2\right)=F_r=-kr$$

$$\frac{d}{dt}\left(mr^2\frac{dq}{dt}\right)=F_q=0$$

when $\frac{dq}{dt}\approx const(F_q\approx 0)$, from energy conservation

$$\frac{m}{2}\left(\left(\frac{dr(t)}{dt}\right)^2-\left(\frac{dr(0)}{dt}\right)^2\right)+\frac{k}{2}\left(r(t)^2-r(0)^2\right)-\frac{m}{2}\left(\left(r\frac{dq}{dt}\right)_t^2-\left(r\frac{dq}{dt}\right)_0^2\right)=0$$

$\frac{dr}{dt}\approx 0$ at a maximum of r(t),
$$\frac{m}{k}=\frac{\left(r(t)^2-r(0)^2\right)}{\left(\frac{dr(t)}{dt}\right)^2-\left(\frac{dr(0)}{dt}\right)^2}$$